

The Magneto-coulomb effect in spin valve devices

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Abstract

We discuss the influence of the magneto-coulomb effect (MCE) on the magnetoconductance of spin valve devices. We show that MCE can induce magnetoconductances of several per cents or more, dependent on the strength of the coulomb blockade. Furthermore, the MCE-induced magnetoconductance changes sign as a function of gate voltage. We emphasize the importance of separating conductance changes induced by MCE from those due to spin accumulation in spin valve devices.

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The recent past has seen an impressive effort in connecting ferromagnetic leads to ever smaller non-ferromagnetic structures. The main idea behind this is to make use of the electron spin for device purposes. In a two-terminal, spin valve geometry, a resistance difference ΔR is expected between two basic situations. First, if the two ferromagnetic leads are magnetized in an anti-parallel fashion, the majority spin species injected at the first ferromagnet is predominantly reflected at the second ferromagnet. This results in a high resistance state. On the other hand, in the case of parallel magnetizations, the injected majority spin couples well to the second ferromagnet, leading to a lower resistance state. With the miniaturization of the central structure, quantum confinement effects come into play. Recently, quite some progress has been made in studying spin devices in the presence of coulomb blockade.^{1,2,3,4,5,6,7,8,9,10,11} The interpretation of the two-terminal data in these reports has mostly focused on spin transport and spin accumulation. Here, we discuss another influence on the two-terminal resistance in ferromagnetically contacted nanostructures, namely the magneto-coulomb effect (MCE) discovered by Ono *et al.*¹². In this contribution, we consider a confined conductor weakly connected to two ferromagnets, F_1 and F_2 (see Fig. 1a). The coupling is described by two sets of resistances and capacitances, R_1, C_1 and R_2, C_2 , respectively. Furthermore, the island can be gated by a voltage V_g via a capacitor C_g . For a basic introduction to the MCE, we first concentrate on one of the ferromagnets only, F_1 , which is assumed magnetized in the positive direction. Let us suppose that a positive external magnetic field ($B > 0$) is applied. In that case, the energy of the spin up(\uparrow) and spin down(\downarrow) electrons shift by the Zeeman energy, in opposite directions (see Fig. 1b). However, for a ferromagnet, the density of states of both spin species differs ($N^\uparrow > N^\downarrow$). Hence, a shift in the chemical potential $\Delta\mu$ needs to take place to keep the number of electrons constant.¹²

$$\Delta\mu = -\frac{1}{2}Pg\mu_B B \quad (1)$$

where the thermodynamic polarization P is defined as $P = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$,¹³ g is the gyromagnetic ratio and μ_B is the Bohr magneton. In practice, however, the ferromagnet will be attached to a macroscopic non-magnetic lead. This demands equal chemical potentials in both metals. Hence, the energy shift in the ferromagnet translates to a change in the contact

potential between the ferromagnet and the normal metal, $\Delta\phi$, according to, $-e\Delta\phi = -\Delta\mu$.¹² Equivalently, one could say that the work function of the ferromagnet changes by $\Delta W = -\Delta\mu$. Since the ferromagnet is weakly coupled to the central island, this shift influences the Coulomb levels of the latter. In fact, an additional charge Δq is induced onto the island due to the contact potential change $\Delta\phi$. Applying a magnetic field thus has an effect that is similar to changing the gate voltage. This equivalence has been beautifully demonstrated by Ono *et al.*¹² For the situation sketched above, we find:

$$\Delta q(B) = \frac{C_1}{2e} P g \mu_B B \quad (2)$$

Hence, if no magnetization rotation or switching takes place in the ferromagnet, the induced charge onto the island changes linearly with the applied field B . Interestingly, for a system in the Coulomb blockade regime, the conductance $G(q)$ is a (more or less periodic) function of the induced charge. Combining $G(q)$ with eq. 2, we find that the conductance changes with field:

$$\Delta G(B) = \frac{dG}{dq} \Delta q(B) \quad (3)$$

For a Coulomb island, $G(q)$ can be calculated (or it can be measured experimentally versus the gate voltage). The exact theory to apply depends on the magnitude of the various energy scales involved.¹⁴ In any case, the sign of ΔG is determined by the signs of both P and $\frac{dG}{dq}$. Since the function $G(q)$ is periodic, $\frac{dG}{dq}$ and ΔG change sign periodically, specifically at a Coulomb peak.

Next, we incorporate magnetization switching. Again, we start with ferromagnet F_1 magnetized in the positive direction, but now we ramp down the external field ($B < 0$). Then, according to eq. 3, the conductance changes linearly with B , as long as the magnetization of the ferromagnet is unchanged. However, when B reaches the coercive field, i.e., $B = -B_c$, the magnetization of the ferromagnet switches to the negative direction. Hence, also Δq changes discontinuously, by $\Delta q_c = \frac{C_1}{e} P g \mu_B B_c$. This results in a jump in the conductance via eq. 3. For more negative B fields, the conductance change will be linear with B again, but now with opposite sign. So far, we

have considered an island connected to one ferromagnet only. The extension to a spin valve device with two ferromagnetic contacts is rather trivial, since their effects can be added. Hence, a conductance change linear in B is expected, with discontinuities at the coercive fields of both ferromagnets.

To illustrate the above, we consider the device in Fig. 1a), where F_1 and F_2 have different switching fields. (This can be achieved by choosing thin strips of different widths).^{15,16,17} To calculate the conductance properties of the system, i.e. $G(q)$, we make use of the orthodox model of coulomb blockade.^{14,18} This choice is rather arbitrary, since eq. 3 can in principle be applied to other regimes of coulomb blockade. In Fig. 2a), we show G vs q for a certain choice of (symmetric) system parameters (see caption Fig. 2).¹⁹ From Fig. 2a) and eq. 3, we infer that the sign and magnitude of the MCE depend critically on two properties: i) the system parameters, which define the sharpness of the Coulomb peaks; ii) the charge state about which Δq applies, which defines the distance to a Coulomb peak. Close to the inflection point of sharp Coulomb peaks, $\frac{dG}{dq}$ can become very large. Therefore, even a small Δq can induce a sizeable resistance change, *without* a fundamental limitation. In principle, effects exceeding 100% are possible.

Next, we determine the field dependence of the conductance in the system considered. We (arbitrarily) evaluate around the charge state $q = 0.69e$, where $dG/dq < 0$ (indicated in Fig. 2). Furthermore, we use $P = -0.6$, which is the thermodynamic polarization of cobalt.^{12,13} In Fig. 3a), we plot the induced charge on the island as a function of magnetic field. Using eq. 3 together with Figs. 2a) and 3a) we obtain the field dependence of the conductance (see Fig. 3b). As discussed above, MCE gives linear conductance changes for fields exceeding the switching fields (giving a 'background magnetoconductance' for large fields). Around the switching fields, however, discontinuous changes are seen which lead to hysteretic behavior. We note that Fig. 3b) does show similarities with several experiments in spin valve devices²⁰. This emphasizes the importance to separate both phenomena.¹⁷ To connect to experiment, we define the conductance change due to MCE, ΔG_{MCE} , as the sum of the two conductance steps at the coercive fields, i.e., $\Delta G_{MCE} = -\frac{dG}{dq}Pg\mu_B(C_1B_{c1} + C_2B_{c2})/e$. We indicate ΔG_{MCE} in Fig. 3b). With this definition, we are able to plot the relative magnetoconductance change $\Delta G_{MCE}/G$ as a function of the charge state (see Fig. 2b)). Since this quantity is proportional to the

logarithmic derivative of the function $G(q)$, it changes sign at the extremes of Fig. 2a).²⁰ Figures 2 and 3 summarize the magnetoresistances that can be expected in two-terminal spin valve structures, as a result of MCE.

Recently, much work has been done to investigate magnetic field induced conductance changes in quantum dot-like structures, such as carbon nanotubes^{1,2,3,4,7,8,9,10,11,21} and small metal islands.^{5,6} In these studies, conductance changes are seen, which are generally interpreted in terms of spin accumulation. However, three phenomena are noteworthy: 1) in many cases, the change in conductance sets in before the magnetic field changes sign, i.e. before the ferromagnetic electrodes switch their magnetization.^{1,2,3,4,5,22} 2) In some studies the magnetoconductance changes sign as a function of gate voltage.^{2,4,21,22} 3) In carbon nanotubes connected to only one ferromagnet (and to gold), field-induced conductance changes are also observed.²³ In the latter system spin detection is clearly not possible.

We believe that in many experiments, MCE plays an important role. As seen in Fig. 2, MCE-induced conductance changes have the following properties: 1) they set in continuously at zero field; 2) they change sign as a function of gate voltage, exactly at the Coulomb peaks; 3) MCE-induced conductance changes also take place for coulomb islands connected to only one ferromagnet, as discussed above. Hence, the combination of MCE with spin accumulation could be responsible for part of the phenomena listed above. We note that the sign changes seen in Refs.^{2,4,21,22} have been explained within (coherent) spin transport models (see also Ref.²⁴). However, in most of these systems coulomb blockade was also observed. This implies that MCE should be taken into account to obtain full correspondence between experiment and theory.

More generally, it is important to separate spin accumulation and MCE (and other magnetoresistances) experimentally. The best way to do this, is by a direct measurement, using a non-local, four-probe geometry¹⁷. This method separates out all magnetoresistances, not only MCE. If a non-local measurement is not possible, the MCE and spin accumulation should be separated in other ways. For example by monitoring the temperature and gate voltage dependence of the relative conductance changes and comparing these data sets to what is expected for MCE. Clearly, the MCE decreases

with a decrease of the conductance peaks. Otherwise, experiments on nanotubes with two ferromagnetic contacts can be compared to those with one ferromagnet and a normal metal.⁴ However, for a proper comparison, it is essential, that the coupling to the normal metal and the ferromagnet is very similar.

Finally, we discuss the influence of a demagnetizing field on the MCE qualitatively. This field may play a significant role in carbon nanotubes onto which a ferromagnetic strip is evaporated. Locally, in the nanotube beneath the ferromagnet, the demagnetizing field is expected to be quite high, of order 0.5 T (assuming a field due to the ferromagnet of 1 T close to its surface). The reason for this is that the aspect ratio of the nanotube is unity (in the radial direction). The demagnetizing field shifts the local work function of the ferromagnet thus adding to MCE. Suppose now that the ferromagnet is magnetized in the positive direction and a negative B field is applied. Then, we expect the ferromagnetic domains in the vicinity of the nanotube to change their orientation slowly. This locally rotates the demagnetization field and therefore changes Δq . As a consequence, a characteristic magnetoconductance trace is expected, with conductance changes setting in *before* the ferromagnet actually switches (cf. Ref.²⁵). As soon as the ferromagnet does switch, we are in a mirror image of the original situation and the contribution of the demagnetizing field jumps back to its old value. We conclude that MCE due to the demagnetizing field gives a continuous conductance change for fields down to the coercive field. Just as for the external-field-induced MCE, conductance changes are already expected at fields close to 0 T. This is consistent with the majority of two-terminal experiments.^{1,2,3,4,5,6,22} In Fig. 3b), we sketch the total MCE, including that of the demagnetizing field (dashed line). We note the similarity of the full MCE curve (though partly qualitative) with what is expected for spin accumulation.²⁶

In summary, we show that the magnetocoulomb effect should be taken into account to explain experiments on spin valve structures in the coulomb blockade regime. A proper separation of spin accumulation and MCE is essential for a good understanding of the first.

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- ¹ K. Tsukagoshi, B. W. Alphenaar and H. Ago, *Nature*, **401** 572 (1999).
- ² K. Tsukagoshi and B. W. Alphenaar, *Superlattices and Microstructures* **27**, 565 (2000).
- ³ S. Sahoo, T. Kontos, C. Schönenberger and C. Sürgers, *Appl. Phys. Lett.* **86**, 112109 (2005)
- ⁴ S. Sahoo, T. Kontos, J. Furer, C. Hoffmann, M. Gräber, A. Cottet and C Schönenberger, *Nature Physics* (2005)
- ⁵ K. Yakushiji, F. Ernult, H. Imamura, K. Yamane, S. Mitani, K. Takanashi, S. Takahashi, S. Maekawa and H. Fujimori. *Nature* **4**, 57 (2005)
- ⁶ L.J. Zhang, C. Y. Wang, Y. G. Wei, X. Y. Liu, and D. Davidovic *Phys. Rev. B* **72**, 155445 (2005)
- ⁷ J. R. Kim, H. M. So, J.J Kim and J. Kim, *Phys. Rev. B.* **66**, 233401 (2002).
- ⁸ S. Chakraborty, K. M. Walsh, L. Liu, K. Tsukagoshi and B. W. Alphenaar, *App. Phys. Lett* **83**, 1008 (2003).
- ⁹ D. Orgassa, G. J. Mankey and H. Fujiwara, *Nanotechnology*, **12**, 281 (2001).
- ¹⁰ B. Zhao, I. Mönch, T. Mühl, H. Vinzelberg, and C. M. Schneider , *J. Appl. Phys.* **91**, 7026 (2002)
- ¹¹ B.W. Alphenaar, S. Chakraborty and K. Tsukagoshi, in *Electron Transport in Quantum Dots* (Kluwer Academic/Plenum Publishers, New York 2003) chap. 11.
- ¹² K. Ono, H. Shimada and Y. Ootuka, *J. Phys. Soc. Jpn* **67**, 2852 (1998); H. Shimada, K. Ono, and Y. Ootuka, *J. Appl. Phys.* **93**(10), 8259 (2003), H. Shimada and Y. Ootuka, *Phys. Rev. B* **64**, 235418 (2001)
- ¹³ For MCE one should consider the thermodynamic quantity P , i.e., P as a result of the full band structure. This P differs considerably from the polarization determined in tunnel experiments, since for the latter tunnel matrix elements play a role as well. For Co, $P \approx -0.6$, whereas for Ni, $P \approx -0.8$. See Ref.¹².
- ¹⁴ L.P. Kouwenhoven et al. Electron transport in quantum dots, Proc. Adv. Study Institute on Mesoscopic Electron transport (L.L. Sohn, L.P. Kouwenhoven and G. Schn, Eds), Kluwer 1997

- ¹⁵ M. Johnson and R.H. Silsbee, *Phys. Rev. Lett.* **55**, 1790 (1985)
- ¹⁶ F.J. Jedema, A. T. Filip and B. J. van Wees, *Nature* **410**, 345 (2001).
- ¹⁷ N. Tombros, S.J. van der Molen and B.J. van Wees, cond-mat/0506538
- ¹⁸ We assume each coulomb peak to be independent. Although this is not exactly correct, it suffices to show the principle of MCE.
- ¹⁹ We use q as a relative quantity, i.e., $q = 0$ corresponds to a situation where N electrons are present on the island (charge $-Ne$). N depends on the properties of the system and can be large. A change in q by e corresponds to a change in coulomb level energy by e^2/C_{tot} (where C_{tot} is the total capacitance of the island).
- ²⁰ We note that Fig. 2b) changes considerably for a sample which exhibits a non-zero background conductance.
- ²¹ H.T. Man, L.J.W. Wever and A.F. Morpurgo, cond-mat/0512505 v1
- ²² B. Nagabhirava, T. Bansal, G. Suanasekera, L. Liu, and B.W. Alphenaar, *preprint*, cond-mat/0510112
- ²³ A. Jensen, J.R. Hauptmann, J. Nygard, and P.E. Lindelof, *Phys. Rev. B* **72**, 035419 (2005)
- ²⁴ A. Cottet, T. Kontos, W. Belzig, C. Schönenberger and C. Bruder, *preprint*, cond-mat/0512176 v1
- ²⁵ M. Brands and G. Dumpich *J. Appl. Phys.* **97**, 114311 (2005)
- ²⁶ We choose a symmetric configuration. However, if asymmetric contacts are assumed (e.g., $C_1 \neq C_2$), the shape of Fig. 2b) will change accordingly. If one of the peaks in Fig.2b) dominates the other, only one peak may be observed experimentally.

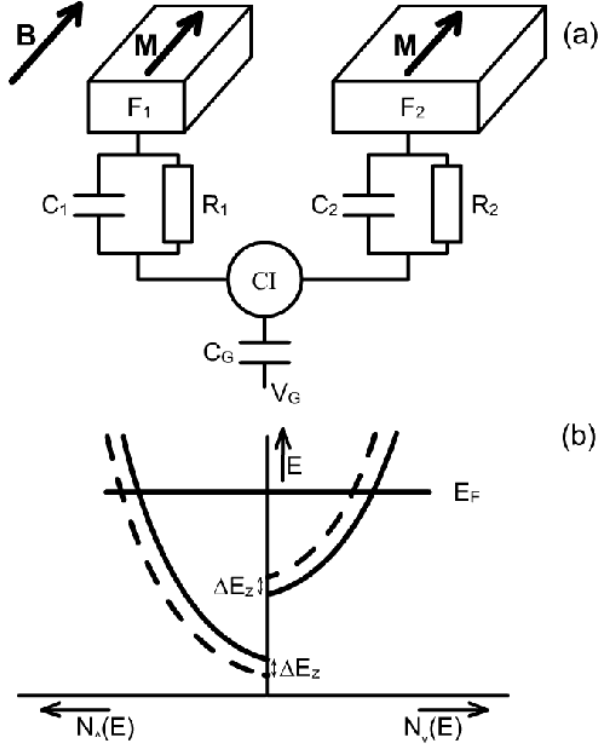


FIG. 1: a) The sample structure considered. Two ferromagnetic strips, F_1 and F_2 , with coercive fields B_{c1} and B_{c2} are weakly connected to a coulomb island (CI) via two tunnel barriers (resistances R_1 and R_2 and capacitances C_1 and C_2). Furthermore, a gate connects capacitively to the island (C_G). b) Sketch of the density of states N of the two spin species in a ferromagnet, versus energy. When a magnetic field is applied, the energies of the two spin species shift (ΔE_z) in opposite directions by the Zeeman effect. Since $N^\uparrow > N^\downarrow$, this results in a change in the work function, ΔW .

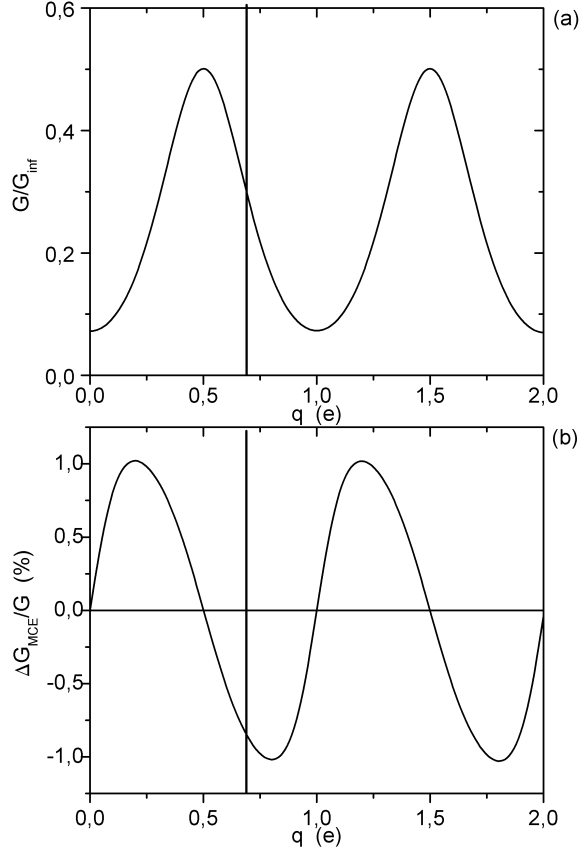


FIG. 2: a) G vs charge state q calculated for the system in Fig. 1a) with parameters: $C_1 = C_2 = 2 \cdot 10^{-17} F$, $C_g = 5 \cdot 10^{-18} F$, $R_1 = R_2 = 2.5 M\Omega$. G is given in units of $G_\infty = 1/(R_1 + R_2) = 0.2 \mu S$ b) Relative conductance change $\Delta G_{MCE}/G$ vs ΔE_F (in %). We use $P = -0.6$, $B_{c1} = 0.09 T$, $B_{c2} = 0.11 T$ and take $g = 2$. Note that the relative resistance change, $\Delta R_{MCE}/R$, equals $-\Delta G_{MCE}/G$. Figure 3 is evaluated at $q = 0.69 e^2/C_{tot}$, indicated by the vertical lines in a) and b).

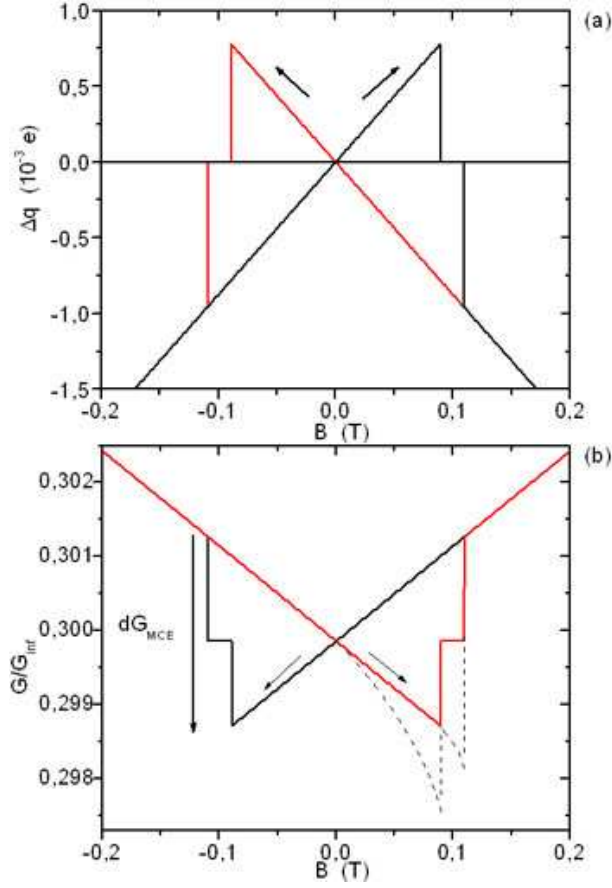


FIG. 3: (Color online) a) Induced charge on the central island, Δq , versus the applied magnetic field (see eq.2). Δq varies linearly with B , except at the switching fields, where steps are seen. The curve ignores the demagnetizing field. b) Influence of the external magnetic field on the zero-bias conductance, calculated with eq. 3. Solid line: demagnetization field ignored. We define the sum of these steps as $\Delta G_{MCE} < 0$. We note that $|\Delta G_{MCE}|$ can become quite large, despite the low values of the induced charge, since it depends critically on the sharpness of the Coulomb peaks (see Fig. 2). Dashed line: qualitative effect of the rotation of the demagnetization field at the nanotube (only drawn for positive fields). Graph a) and b) are evaluated at $q = 0.69e$, indicated in Fig. 2